

An Archean Biosphere Initiative. A. D. Anbar¹, E.S. Boyd², R. Buick³, M. Claire³, D. DesMarais⁴, D. Domagal-Goldman³, J. Eigenbrode⁵, D. Erwin⁶, K. Freeman⁷, R. Hazen⁸, C. Johnson⁹, T. Lyons¹⁰, V. Meadows³, H. Ohmoto⁷, S. Ono¹¹, J.W. Peters², B. Shapiro⁷, R. Summons¹¹ and M. Walter¹². ¹Arizona State University, Tempe, AZ, 85287, USA. ²Montana State University, Bozeman, MT, 59717. ³University of Washington, Seattle, WA, 98195, USA. ⁴NASA Ames Research Center, Moffett Field, CA, 94035, USA. ⁵NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA. ⁶Smithsonian Institution, Washington, DC, 20560, USA. ⁷Pennsylvania State University, Univ Pk, PA, 16802, USA. ⁸Carnegie Institution of Washington, Washington, DC, 20015, USA. ⁹University of Wisconsin, Madison, WI, 53706, USA. ¹⁰University of California, Riverside, CA, 92521, USA. ¹¹Massachusetts Institute of Technology, Cambridge, MA, 02139, USA. ¹²University of New South Wales, Sydney, NSW, 2052, Australia.

The search for life on extrasolar planets will necessarily focus on the imprints of biology on the composition of planetary atmospheres. The most notable biological imprint on the modern terrestrial atmosphere is the presence of 21% O₂. However, during most of the past 4 billion years, life and the surface environments on Earth were profoundly different than they are today. It is therefore a major goal of the astrobiology community to ascertain how the O₂ content of the atmosphere has varied with time, and to understand the causes of these variations.

The NAI and NASA Exobiology program have played critical roles in developing our current understanding of the ancient Earth's atmosphere, supporting diverse observational, analytical, and computational research in geoscience, life science, and related fields. In the present incarnation of the NAI, ongoing work is investigating (i) variations in atmospheric O₂ in the Archean to the Cambrian, (ii) characterization of the redox state of the oceans shortly before, during and after the Great Oxidation Event (GOE), and (iii) unraveling the complex connections between environmental oxygenation, global climate, and the evolution of life.

However, there is no comprehensive umbrella under which such research is coordinated and extended deeper back in time into the Archean record. Additionally, compared to prior incarnations of the NAI, in the wake of CAN5 there is less effort devoted to understanding the reason for the generally anoxic state of the Earth during the first half of its history. Because such research requires integration of paleoenvironmental and paleobiological lines of evidence, as well as integration of geochemical observations with laboratory experiments and theoretical models, a strategic initiative focused on the Archean biosphere and Earth's evolution up to the GOE would leverage current efforts and past investments by NASA and the NAI. This is an area ripe for further development, particularly in light of findings that have been published in the past 24 months by multiple groups. These findings collectively point to the possibility that small but significant amounts of O₂ were produced biologically at least 100 Ma before the GOE, and possibly much earlier, and

that a key geochemical proxy of atmospheric anoxia – “MIF-S” – requires further investigation and calibration. The rapid development of genomic databases also opens the door to novel explorations of metabolic evolution.

We propose the creation of an Archean Biosphere Initiative (ABI) to catalyze interactions between NAI teams and between the NAI and outside researchers to better understand the evolution of the Archean biosphere, with a special focus on the early evolution of O₂ in the environment. The ABI would be a concerted effort to integrate investigations into the geologic and genomic records, modern natural analog systems, experiments and models, meshing the interests and capabilities of a number of teams including (at least) the ARC, ASU, MIT, MSU, PSU, UW, ARC, Carnegie, GSFC and VPL@UW teams and the ACA, as well as key researchers from outside the NAI.

The mission-relevance of the ABI is that it will inform the development of Archean ocean-atmosphere biogeochemical models that can be used to interpret spectra from Earth-like planets around other stars. Such models are being developed by the VPL@UW team and other groups outside the NAI. In addition, furthering our understanding of the evolution of the Earth system is relevant to astrobiology missions to planets and moons in our Solar System in that it provides a conceptual framework for grounding exploration for potential biospheric evolution elsewhere.

The proximal goal of the ABI is to determine the chronological sequence of evolution of key metabolisms and specific lineages, particularly those relevant to the evolution of oxygenic photosynthesis, in the context of their co-evolution with the environment. These metabolisms and lineages include:

- oxygenic photosynthesis
- anoxygenic photosynthesis
- dissimilatory sulfate reduction
- nitrogen fixation
- denitrification
- methanogenesis

- methanotrophy (anaerobic or aerobic)
- dissimilatory iron reduction
- eukaryotes
- cyanobacteria

To achieve the necessary integration, the ABI would undertake two critical types of activities:

1. The ABI would begin to distill and organize the state of understanding of the Archean biosphere, in the form of on-line databases, knowledge summaries on key topics and critical inventories of key samples (including but not limited to those obtained in the last 5 years by the Astrobiology Drilling Program). This ongoing activity would highlight the gaps in understanding where incremental efforts could make a major difference. The inspiration for these activities is the "PPRG" (Precambrian Paleobiology Research Group) effort of 30 years ago. This effort remains extraordinarily influential to the present day and is the sort of activity that requires the sustained support of an entity like the NAI.
2. The ABI would catalyze the development of integrative research concepts that would be proposed to the NAI DDF or other funding opportunities. This would occur through the efforts of a small steering group; annual in-person meetings and workshops centered on particular research themes; and occasional field workshops. In-person meetings and workshops would be charged with developing deliverable materials for dissemination via the ABI web site, review papers or other means, as well as DDF-scale proposal concepts. In this way, the efforts of the ABI would be more directed than those of a typical NAI "focus group".

Discussions at the 2009 NAI Tempe Workshop identified four areas particularly ripe for integrative research in the near term. These include, in no particular order:

Area #1: Elucidating Metalloprotein Evolution.

Correlate the evolutionary history of metalloprotein-encoding genes that are indicative of functional processes with changes in the availability of transition elements (Fe, Ni, Mo, etc.) in Precambrian oceans. The connection between the evolution of functional processes and geospheric evolution centers primarily on the fact that the availability of many transition metals required for metalloproteins changed with environmental oxygenation.

Area #2: Linking Atmosphere and Aqueous Geochemistry Models. Build a bridge between models of the chemistry of oxidative weathering and models of late Archean atmospheric chemical evolution. Models of late Archean oxidative weathering reveal the minimum amount of dissolved O₂ needed to weather sulfide minerals, uranium oxide and a variety of rock types. Models of late Archean atmospheric chemistry identify the maximum amount of ground-level O₂ that could have been sustained in an otherwise reducing atmosphere. Hence, it is natural to seek to link such models.

Area #3: Integrating Geochemical and Paleobiological Investigations. Coordinated geochemical and paleobiological investigations of fossil microbial ecosystems and associated sediments are surprisingly rare. Studies by geochemists and paleobiologists are often disconnected, with inadequate coordination of sample locations, specific materials analyzed, etc., and slow iteration between geochemical and paleobiological modeling efforts.

Area #4: Calibrating Paleoproxies and Processes. A host of proxies for studying life and environment in Archean rocks have been developed in the past decade, many of which have been catalyzed by the NAI. These include: isotopic and elemental tracers of particular metabolisms and environmental redox states; molecular organic biomarkers; in situ elemental and isotopic analytical analyses; etc. However, our ability to interpret these signatures is typically limited by our ability to relate signatures in ancient rocks to biological environmental variables. In some cases, we need better laboratory experiments to determine isotope fractionation factors (e.g., mass-dependent and -independent isotope effects for O, S, Fe, Ni, Mo, Hg, and U), element partition functions, molecular products of metabolism, etc. In other cases, we need more studies in modern sediments and the recent geologic record to understand how primary signatures are altered by diagenesis, an understanding that is critical for successful application of paleoproxies. Numerous studies are possible under this umbrella, many of which would cut across the NAI.